January 23, 2013

Impact of Torsion Space-Time on $t\bar{t}$ observables at Hadron Colliders

Seyed Yaser Ayazi and Mojtaba Mohammadi Najafabadi

School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran

Abstract

Starting from the effective torsion space-time model, we study its effects on the top pair production cross section at hadron colliders. We also study the effect of this model on top pair asymmetries at the Tevatron and the LHC. We find that torsion space-time can explain forward-backward asymmetry according to measured anomaly at Tevatron. We find an allowed region in the parameters space which can satisfy simultaneously all $t\bar{t}$ observables measured at Tevatron and LHC.

1 Introduction

Top quark physics is one of the most promising probe of beyond Standard model (SM) since top quark is the heaviest known particle and is copiously produced at hadron colliders. A very large number of top quarks are produced at the LHC eventually more than 10^7 $t\bar{t}$ pairs per year [1]. Moreover, due to the large mass of the top quark which is at the order of the electroweak symmetry breaking, its lifetime is very short. This feature causes that it decays before hadronzation and provides opportunity to explore precision test of the SM and its various properties like charge, mass and spin.

Experimental results for the cross section of top pair at Tevatron and LHC are well consistent with the SM prediction. Another important measurement for top quark production is top Forward-Backward Asymmetry

(FBA) at Tevatron. The CDF and D0 collaborations reported sizable measurement difference with SM prediction [2, 3] for FBA. Actually, this observation at Fermilab Tevatron may already be a hint of new physics. In the SM, top pair production can be produced via the $q\bar{q}$ annihilation and gg-fusion. The interference between radiative corrections involving gluon emission and also the interference of leading order diagram with box diagrams lead to FBA in the top pair production [4].

Since the initial state of proton-proton collisions at the LHC is symmetric, FBA is not observed but another asymmetry can be observed (Charge Asymmetry) [4]. Charge Asymmetry (CA) at the LHC is defined as the difference between events with positive and negative absolute values of rapidities of top and antitop quarks. The CMS collaboration has recently presented CA measurement in $t\bar{t}$ production at the LHC for the center-of-mass energy of 7 TeV and 1.09 fb^{-1} of data. This measurement is well consistent with the SM prediction. Nevertheless, the measurement of CA at LHC can provide an independent criterion to search for NP models which explain FBA at Tevatron. It seems difficult to explain the size and nature of FBA by any new extension of SM. Because experimental constraint from Tevatron and LHC on parameters space of this theories, must be simultaneously satisfied and there is a correlation between Tevatron FBA and LHC CA.

Despite the impressive success of SM, common point of view is that SM can not play the role of fundamental theory because at least it does not include quantum gravity. Therefore, desired fundamental theory is expected to provide the solution to the quantum gravity and maybe even explain the low energy observables. Traces of such fundamental theories could be identified by some additional characteristics of the space-time, different from the SM fields. Space-time torsion is one of the candidates which can play this role. So far, the effect of torsion space-time on low-energy experiment

have been studied in the literature [5].

In order to explain the measured FBA, many extensions of SM have been proposed. Some of these models propose unknown heavy particles which can be exchanged in top pair production process [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. In this paper, taking into account the possibility of torsion field effect on top pair production at hadron colliders and the consistency of this theory with all observables specially with FBA is studied.

The rest of this paper is organized as follows: In the next section, we introduce effective approach to torsion and study effect of torsion field on top pair production at hadron colliders. In section 3, we summarize observables which we study at the LHC and Tevatron and study the effects of torsion field exchange in production of $t\bar{t}$ at Tevatron and LHC. We also calculate torsion effect on forward-backward top pair asymmetry at Tevatron and charge asymmetry at the LHC. This enable us to put the constraint on parameters space of torsion extension the SM by using the present experimental measurements. The conclusions are given in section 4.

2 The space-time Torion and its phenomenological aspects

In this section, we briefly review notation of the gravity with torsion and quantum theory of matter fields in the external torsion field. In the following, we study the effects of torsion space-time on our observable specially top pair production at Tevatron and LHC.

In the theory with torsion field, $T^{\alpha}_{\beta\gamma}$ is defined as follows[16]:

$$T^{\alpha}_{\beta\gamma} = \Gamma^{\alpha}_{\beta\gamma} - \Gamma^{\alpha}_{\gamma\beta}, \tag{1}$$

where $\Gamma^{\alpha}_{\beta\gamma}$ are the christopher symbols. In general case the torsion field can be presented in the irreducible components[17]

$$T_{\alpha\beta\gamma} = \frac{1}{3}T_{\beta}g_{\alpha\gamma} - T_{\gamma}g_{\alpha\beta} - \frac{1}{6}\varepsilon_{\alpha\beta\gamma\delta}S^{\delta} + q_{\alpha\beta\gamma}, \tag{2}$$

where the axial vector $S^\delta = \varepsilon^{\alpha\beta\gamma\delta} T_{\alpha\beta\gamma}$, T_α is a vector trace of torsion and $q_{\alpha\beta\gamma}$ is a tensor which satisfies the constraints $q^\alpha_{\beta\alpha} = 0$ and $q_{\alpha\beta\gamma}\varepsilon^{\alpha\beta\gamma\delta} = 0$.

In this paper, we calculate the contribution of exchange of torsion field to top pair production at hadron colliders. Let us now consider the interaction of Dirac spinor ψ as external gravitational field with torsion which has the following form:

$$S_f = \int d^4x\sqrt{g}\{i\overline{\psi}\gamma^\mu(\nabla_\mu - i\eta_1\gamma^5 S_\mu + i\eta_2 T_\mu)\psi - m\overline{\psi}\psi\}, \tag{3}$$

where η_1 and η_1 are non-minimal parameters and ∇_μ is Riemannian covariant derivative without torsion. For special case of minimal coupling this expression corresponds to the values $\eta_1 = -1/8$ and $\eta_2 = 0$. It is shown in [18] that for a fixed non-zero value of η_1, this action is not renormalizable while the zero value for η_2 does not imply any difficulties. In this paper, we consider η_1 as an arbitrary parameter and take $\eta_2 = 0$. Therefore, the interaction between a Dirac field, with torsion is described by following action:

$$S_{TS-matter} = i\int d^4x\sqrt{g}\overline{\psi}_i(\gamma^\alpha\nabla_\alpha + i\eta_i\gamma^5\gamma^\mu S_\mu - im_i)\psi_i, \tag{4}$$

where η_i is the non-minimal interaction parameter for corresponding spinor. Notice that this action corresponds to the complementary antisymmetric torsion $T_{\alpha\beta\gamma} = -\frac{1}{6}\varepsilon_{\alpha\beta\gamma\delta}S^\delta$. In our case, we suppose that the metric is flat $g_{\mu\nu} = \eta_{\mu\nu}$. Unitarity and renormalizability conditions in effective low energy quantum field theory lead to free torsion action with this form:

$$S_{TS-free} = \int d^4x(-\frac{1}{4}S_{\mu\nu}S^{\mu\nu} + \frac{1}{2}M^2_{TS}S_\mu S^\mu), \tag{5}$$

where M_{TS} is the mass of torsion and $S_{\mu\nu} = \partial_\mu S_\nu - \partial_\nu S_\mu$. As it has been seen in (Eq .4), we can enter spinor-torsion interaction to SM as interactions between fermions with a new vector field S_μ. Therefore, the total action include $\mathcal{L}_{SM}$, $\mathcal{L}_{TS-matter}$ and $\mathcal{L}_{TS-free}$. In low energy limit, the total action leads to four fermions interaction term

$$\mathcal{L}_{int} = -\frac{\eta_a\eta_b}{M^2_{TS}}(\overline{\psi}_a\gamma_5\gamma^\mu\psi_a)(\overline{\psi}_b\gamma_5\gamma_\mu\psi_b), \tag{6}$$

where η_a and η_b are dimensionless coupling constants. Therefore, the new four fermions interaction is characterized by dimensionless parameters η_a, η_b and mass of the torsion field M_{TS}. In the following, we consider η_a, η_b and M_{TS} as arbitrary parameters and study the effect of exchange of torsion field on top pair production at the Tevatron and the LHC. The leading order (LO) processes for the production of top pair at hadron colliders include these two processes $q\overline{q} \to t\overline{t}$ and $gg \to t\overline{t}$. We neglect interaction between non-abelian gauge fields (gluons) with torsion since interaction of purely antisymmetric torsion with gauge field does not save gauge invariant[16]. Moreover, torsion field does not have color quantum number and then it can not couple with gluons.

We have calculated the $q\overline{q} \to t\overline{t}$ including the above four fermion effects. When $q\overline{q}$ is the initial state, the amplitude for top pair production is given by:

$$|\mathcal{M}|^2_{TS} \quad = \frac{16\eta_t^2\eta_q^2 s}{M_{TS}^4}[1-(\sqrt{1-\frac{4m_q^2}{s}})\beta\cos\theta]^2, \tag{7}$$

where s is partonic center-of-mass energy, $\beta = \sqrt{1-4m_t^2/s}$, m_t and m_q are the top quark and q quark masses. In Eq. 7, θ is the production angle in the center-of-mass system . Another contribution to this process arises from the interference between SM contribution and torsion effects. Amplitude for this interference given by:

$$\frac{256\eta_t\eta_q g_s^2}{3M_{TS}^2}[1-(\sqrt{1-\frac{4m_q^2}{s}})\beta\cos\theta]^2, \tag{8}$$

where g_s is the strong coupling constant. As we can see in the above amplitudes, the only quantity which appear in this approach is the ratio $\frac{\eta_t\eta_q}{M_{TS}^2}$ and therefore for heavy torsion field the phenomenological consequences depend only on this single parameter.

3 Observables and Numerical results

In this section, we study the total cross section of top pair production at the Tevatron and LHC and consider top pair forward backward asymmetry and charge asymmetry as observables and study the effect of torsion field on them.

Top pair production cross section at the Tevatron (by D0 collaboration[19]) and LHC (by CMS experiment [20]) have been measured to be:

$$\sigma_{\text{Tevatron}}(pp \to t\bar{t}) \quad = 7.56 \pm 0.83 \; [pb] \; (\text{stat} \oplus \text{sys}), \tag{9}$$

$$\sigma_{\text{LHC}}(pp \to t\bar{t}) \quad = 165.8 \pm 13.3 \; [pb] \; (\text{stat} \oplus \text{sys}). \tag{10}$$

These measurements are in good agreement with the SM prediction [21, 22]. The total cross section of top pair production at hadron colliders can be obtained by convoluting the partonic cross section with the parton distribution functions (PDF) for the initial hadrons. To calculate $\sigma(pp \to t\bar{t})$, we have used the MSTW parton structure functions [23] and set the center-of-mass energy to 7 TeV for the LHC and 1.96 TeV for the Teavatron. The total cross section for production of $t\bar{t}$ is given by:

$$\sigma(pp \to t\bar{t}) \quad = \quad \sum_{ab} \int dx_1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \widehat{\sigma}(ab \to t\bar{t}), \tag{11}$$

where $f_{a,b}(x_i, Q^2)$ are the parton structure functions of proton. x_1 and x_2 are the parton momentum fractions and Q is the factorization scale.

Here, we emphasis that for proton-antiproton collision FBA is measured by using invariant difference of t and $\bar{t}$ rapidities. The rapidity y of the top quark is given by:

$$\frac{1}{2} \ln(\frac{E + p_z}{E - p_z}) \tag{12}$$

with E being the total top quark energy and p_z is the top quark momentum along beam axis. The definition of FBA is identical to asymmetry in the

top production angle in the $t\bar{t}$ rest frame:

$$A_{FB} = \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)} \tag{13}$$

As it is mentioned, the SM prediction for FBA is as small as a few percent which arises from the interference between the Born amplitude for $q\bar{q} \to Q\bar{Q}$ and box diagrams and the interference term between initial state radiation and final state radiation [4]. At the Tevatron, since the initial state is asymmetric (proton-antiproton collisions), the top quark forward-backward asymmetry can be measured. Recent measurements by CDF[2] ($A_{FB} = 0.158 \pm 0.075$) and D0[3] ($A_{FB} = 0.196 \pm 0.065$) collaborations shows deviation from the SM prediction which is about 2σ larger than the SM (value about 8%) predictions. At the LHC, initial state is symmetric (proton-proton collisions), as a result FBA vanishes. However, charge asymmetry in $t\bar{t}$ production at LHC can be measured which reflects the top quark rapidity distribution. The top quark charge asymmetry in $t\bar{t}$ is defined by [25]

$$A_C = \frac{N_t(\Delta(y^2) > 0) - N_t(\Delta(y^2) < 0)}{N_t(\Delta(y^2)) > 0 + N_t(\Delta(y^2) < 0)} \tag{14}$$

where $\Delta(y^2)$ is defined by,

$$\Delta(y^2) = (y_t - y_{\bar{t}}).(y_t + y_{\bar{t}}). \tag{15}$$

Rapidity difference is a boost invariant observable while summation of rapidities is not boost invariant and can be written as:

$$y_t + y_{\bar{t}} = \frac{1}{2}\ln(\frac{x_1}{x_2}), \tag{16}$$

where x_1 and x_2 are the parton momentum fractions.

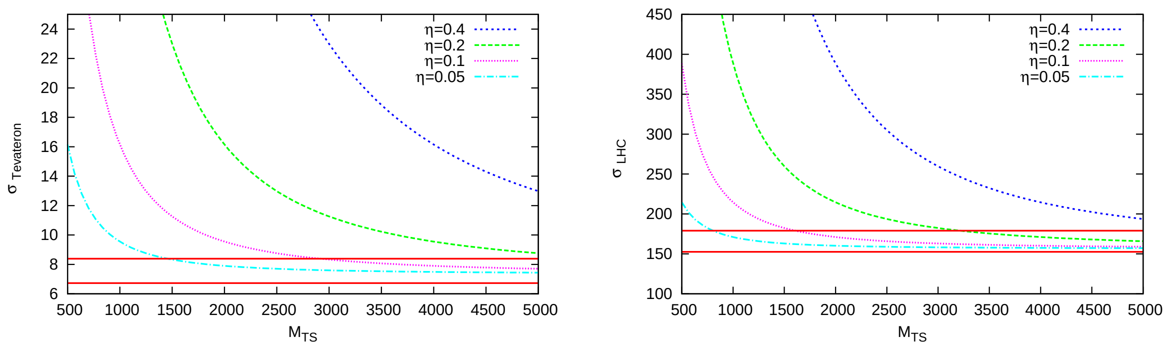
In proton-proton collisions at the LHC, the rapidity distributions of the top and antitop quarks are symmetrically distributed around zero. But since the u, d valence quarks carry larger average momentum fraction than the

anti-quarks, $t\bar{t}$ has a boost along the direction of the incoming quark, and therefore this leads to a larger average rapidity for top quarks than anti-top quarks. The ATLAS and CMS measurements for the charge asymmetry are: $A_C = -0.019 \pm 0.036$ [24], $A_C = -0.013 \pm 0.041$ ($A_C = 0.004 \pm 0.014$) [25] , and the SM prediction is $A_C = 0.0115$ [26]. Notice that while measurements of the FBA show a deviation from the SM expectations, measurement of charge asymmetry at the LHC is in agreement with SM prediction. It means that any new physics which explains the $t\bar{t}$ forward-backward asymmetry must satisfy A_C measurements consistent with the SM predictions. We are also interested in the differential cross section as a function of invariant mass $M_{t\bar{t}} = \sqrt{(p_t + p_{\bar{t}})^2}$, where p_t and $p_{\bar{t}}$ are the four-momenta of top and anti-top, respectively. This quantity is defined by

$$\begin{aligned} \frac{d\sigma(pp \to t\bar{t})}{dM_{t\bar{t}}} &= \sum_{ab} \int_{\frac{M_{t\bar{t}}^2}{E_{CMS}^2}}^{1} dx_1 [f_a(x_1, Q^2) f_b(\frac{M_{t\bar{t}}^2}{x_1 E_{CMS}^2}, Q^2) \\ &\times \frac{2M_{t\bar{t}}^2}{x_1 E_{CMS}^2} \widehat{\sigma}(ab \to t\bar{t})], \end{aligned} \tag{17}$$

As it is mentioned, physical observables related to torsion field depend on the the mass of torsion M_{TS} and coupling constant between torsion and fermion field η_ψ. In [27], a search for narrow resonances has been performed by CMS experiment at LHC and any resonance below 1 TeV has been excluded. In this paper, we consider mass of torsion field in energy scale more than 1 TeV. For the sake of simplicity, we choose identical couplings for interaction between torsion field and fermions. This assumption enables us to put the limit in two dimensional parameters space ($M_{TS} - \eta$) using the present experimental measurements.

To perform our analysis, we have set $m_t = 172.5$ GeV and fixed renormalization and factorization scale $\mu_R = \mu_F = m_t$. For including higher order QCD effects, we have normalized the cross section to the ratio of measured experimental cross section and the leading order SM cross section.



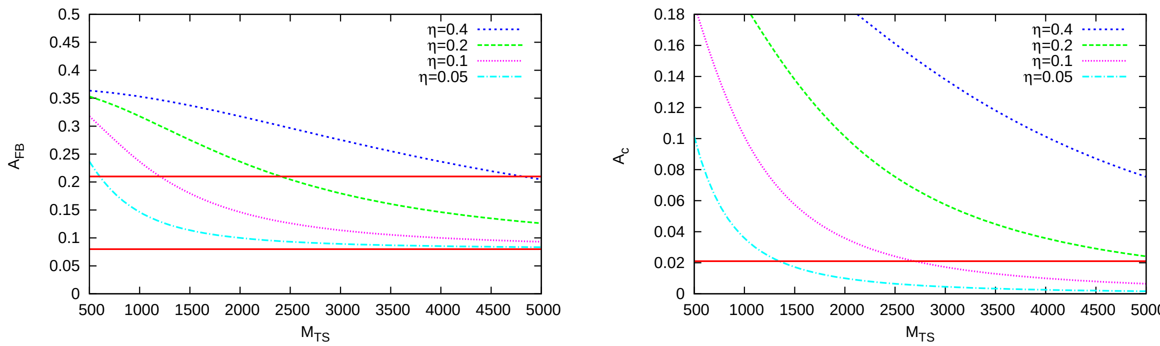
(a) (b)

Figure 1: The top pair production cross section as a function of the torsion mass at Tevatron (a) and LHC (b). The horizontal red lines show allowed range of experimental measurements for the top pair total cross section.

In Fig. 1, we have displayed the total cross section of top-antitop production at the Tevatron and LHC as a function of torsion field mass. The curves with different colors and lines show various values of constant coupling η.

Fig. 2-a(b) depicts $A_{FB}(A_C)$ at Tevatron (LHC). Different values for couplings have been considered. As it can be seen, for instance the allowed values for $\eta = 0.2$ in $A_{FB}(A_C)$ curves are satisfied for $M_{TS} > 1200$ GeV ($M_{TS} > 2600$ GeV). This means that for a given value $\eta = 0.2$, there are allowed regions in parameters space which are consistent with top asymmetries measurements.

The dependence of A_{FB} on invariant mass of $t\bar{t}$ are studied in Fig. 3. In this figure, we display a histogram which depicts forward-backward asymmetry as a function of invariant mass $t\bar{t}$ with seven bins. The green distribution shows SM expectation at to next leading order and red distribution shows measured data at Tevatron [28]. The uncertainties on the data contain statistical and systematics. The blue graph shows torsion model prediction in each bin. To draw this histogram, we set $\eta = 0.12$ and $M_{TS} = 3$ TeV. This histogram compare the experimental measurement at Tevatron and



(a) (b)

Figure 2: The Top pair asymmetries as a function of torsion mass. a) Forward-Backward asymmetry at Tevatron. b) Charge asymmetry at LHC. The horizontal red lines show the allowed ranges of experimental measurements for asymmetries.

SM (NLO) with torsion model prediction. It is remarkable that the SM predictions in each bin are far from measured data at Tevatron and torsion prediction is approximately correspond with data.

We perform a χ^2-fit for forward-backward asymmetry as a function of invariant mass $t\bar{t}$ system ($M_{t\bar{t}}$). This quantity has been defined as:

$$\chi^2 = \sum_i \left(\frac{(A_{FB})_i - (A_{FB}^{exp})_i}{(\sigma^{exp})_i}\right)^2, \tag{18}$$

where summation is over all bins of invariant mass. The size of bins have been chosen according to bins in Fig. 3. In Fig. 4, we show range of parameters space in torsion mass of M_{TS} and coupling constant η plane which are consistent with 68% C.L and 90% C.L. The green area shows regions with 1 σ (68%C.L) and yellow area depicts regions with 1.7 σ (90%C.L) deviation from measured data in global analyze.

Another observable which can help us to study torsion space-time effects on top pair production is differential cross section. Fig. 5 depicts differential cross section of $t\bar{t}$ production at Tevatron as a function of invariant mass $t\bar{t}$ system. The green distribution shows SM expectation at to next leading

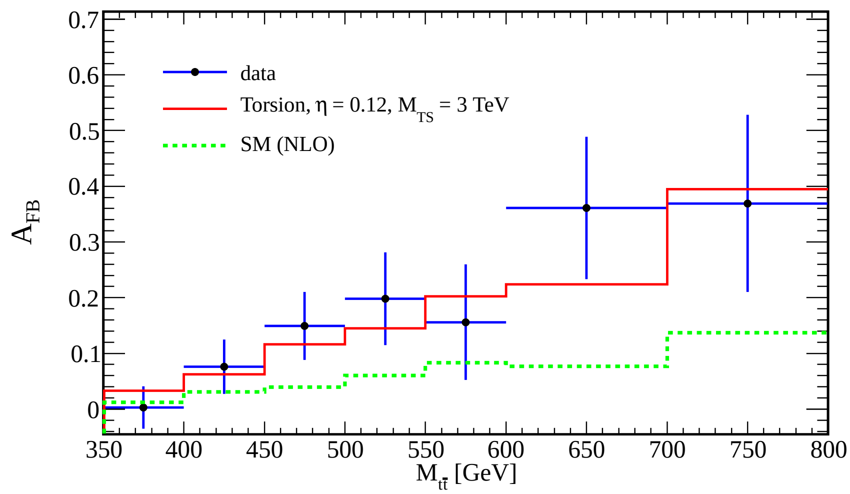


Figure 3: Forward-backward asymmetry as function of invariant mass $M_{t\bar{t}}$ for torsion model compared to the experimental measurement at Tevatron and SM (NLO) expectation.

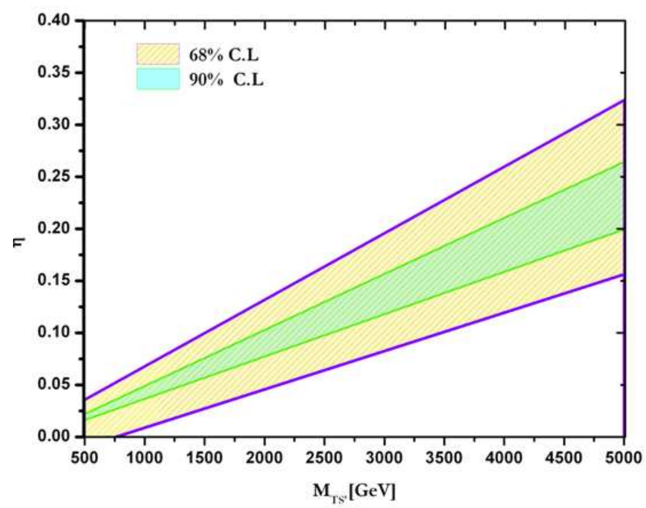


Figure 4: Shaded areas depict ranges of parameters space in torsion mass M_{TS} and coupling constant plane for which are consistent with 68% C.L and 90% C.L.

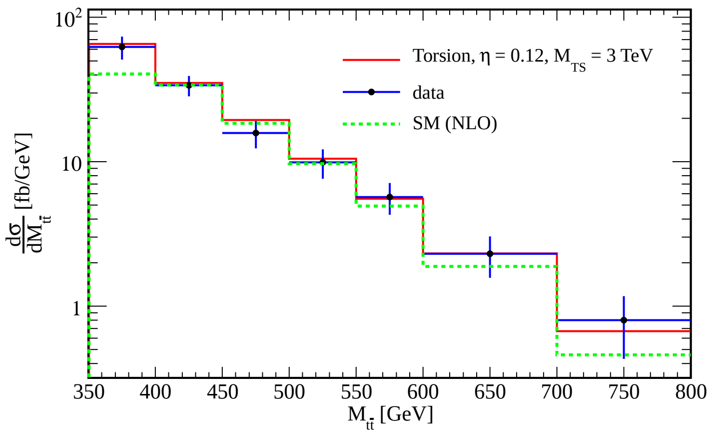


Figure 5: Differential cross section of top-antitop production at the Tevatron as a function of invariant mass $M_{t\bar{t}}$ for torsion model compared to the experimental measurement at Tevatron and SM (NLO) expectation.

order and red distribution shows measured data at Tevatron [29]. The uncertainties on the data contain statistical and systematics and luminosity. The blue graph shows torsion model prediction in each bin. To draw this histogram, we set $\eta = 0.12$ and $M_{TS} = 3$ TeV. This histogram compare the experimental measurement at Tevatron and SM (NLO) with torsion model prediction. As it is shown, the consistency between torsion model prediction with measurement is reasonable.

As it was mentioned in explanation of Fig. 2, there are allowed regions in parameters space which are consistent with top asymmetries measurements. However, this result may conflict with allowed regions for cross section measurement at Tevatron and LHC. To better study of all parameters space which can simultaneously satisfy experimental constraints on σ_{Tevatron}, σ_{LHC}, A_{FB} and A_C, we display Figs. 6. In Fig. 6, the shaded areas depict ranges of parameters space in torsion mass M_{TS} and coupling constant plane for which prediction of effect of torsion space-time on observables σ_{LHC}, σ_{Tev}, A_{FB} and A_{C} are consistent with experimental measure-

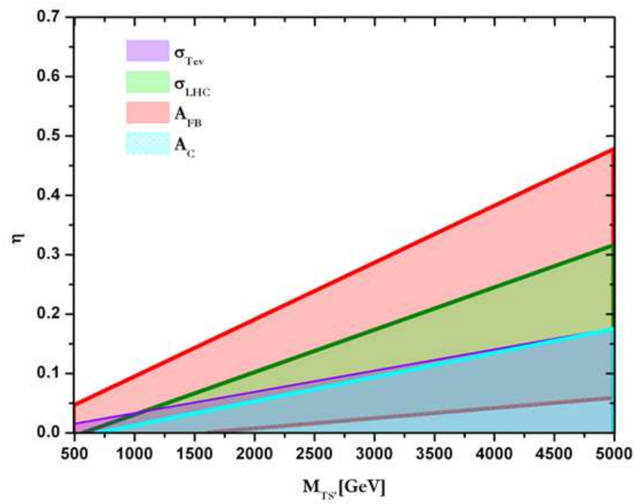


Figure 6: Shaded areas depict ranges of parameters space in torsion mass M_{TS} and coupling constant plane for which are consistent with experimental measurements of observables: $\sigma_{\rm LHC}$, $\sigma_{\rm Tev}$, $A_{\rm FB}$ and $A_{\rm C}$.

ments. It is notable that the allowed regions of top pair production cross section at the LHC and Tevatron, overlap with allowed regions of A_C and A_{FB}. Also there is an overlapping regions between the measured A_C at LHC and measured A_{FB} at Tevatron which increases at high torsion mass M_{TS}. It is remarkable that we find regions in torsion parameters space which all experimental measurement are simultaneously satisfied. This means torsion model can explain measured forward-backward anomaly at Tevatron and top pair cross section measurement and charge asymmetry measurement at LHC can not exclude this model within the present uncertainty.

4 Concluding remarks

In this paper, we have studied the effects of torsion space-time on top pair asymmetries and the cross section productions at the Tevatron and the LHC. We studied the dependence of A_{FB} on invariant mass of $t\bar{t}$. It is shown

that prediction of torsion model is more consistent with measured data at Tevatron than SM prediction for A_{FB} in each bins of $M_{t\bar{t}}$. We performed global χ^2-fit on forward-backward asymmetry as a function of invariant mass $M_{t\bar{t}}$ and showed regions with 1 σ and 1.7 σ deviation from measured data in effective torsion model. We also investigate the differential cross section of $t\bar{t}$ production as independent observable and showed the consistency of this observable for torsion model with data.

Lastly, We have found overlapping regions in parameters space of torsion space-time which all experimental measurement ($\sigma_{\rm LHC}$, $\sigma_{\rm Tev}$, $A_{\rm FB}$ and $A_{\rm C}$) are simultaneously satisfied. This means torsion model can explain measured forward-backward anomaly at Tevatron and top pair cross section measurement and charge asymmetry measurement at LHC can not exclude this model.

5 Acknowledgement

S. Y. A would like to acknowledgement CERN theory division for their hospitality.

References

[1] F. -P. Schilling, Int. J. Mod. Phys. A **27** (2012) 1230016 [arXiv:1206.4484 [hep-ex]].

[2] T. Aaltonen et al.[CDF Collaboration], Phys. Rev. D83, 112003(2011).

[3] V. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 84, 112005 (2011), arXiv:1107.4995 [hep-ex].

[4] J. H. Kuhn and G. Rodrigo, Phys. Rev. D **59** (1999) 054017 [hep-ph/9807420].

[5] A. S. Belyaev and I. L. Shapiro, Nucl. Phys. B **543** (1999) 20 [hep-ph/9806313]; A. S. Belyaev and I. L. Shapiro, Phys. Lett. B **425** (1998) 246 [hep-ph/9712503]; A. S. Belyaev, I. L. Shapiro and M. A. B. do Vale, Phys. Rev. D **75** (2007) 034014 [hep-ph/0701002]; N. E. Mavromatos and A. Pilaftsis, arXiv:1209.6387 [hep-ph]; U. Mahanta and S. Raychaudhuri, hep-ph/0307350; P. Das, U. Mahanta and S. Raychaudhuri, hep-ph/0211137; L. C. Garcia de Andrade, hep-ph/0110361; S. Mohanty and U. Sarkar, Phys. Lett. B **433** (1998) 424 [hep-ph/9804259].

[6] J. A. Aguilar-Saavedra and M. Perez-Victoria, JHEP **1109** (2011) 097 [arXiv:1107.0841 [hep-ph]]; J. A. Aguilar-Saavedra, arXiv:1202.2382 [hep-ph]; P. Ko, arXiv:1202.0367 [hep-ph]; J. A. Aguilar-Saavedra and M. Perez-Victoria, Phys. Rev. D **84** (2011) 115013 [arXiv:1105.4606 [hep-ph]]; M. I. Gresham, I. -W. Kim and K. M. Zurek, Phys. Rev. D **85** (2012) 014022 [arXiv:1107.4364 [hep-ph]].

[7] S. Jung, H. Murayama, A. Pierce and J. D. Wells, Phys. Rev. D **81** (2010) 015004 [arXiv:0907.4112 [hep-ph]]; S. Y. Ayazi, arXiv:1207.0643 [hep-ph]. M. Frank, A. Hayreter and I. Turan, Phys. Rev. D **84** (2011) 114007 [arXiv:1108.0998 [hep-ph]]; J. -Y. Liu, Y. Tang and Y. -L. Wu, J. Phys. G G **39** (2012) 055003 [arXiv:1108.5012 [hep-ph]]; M. Endo and S. Iwamoto, arXiv:1110.0014 [hep-ph].

[8] N. Craig, C. Kilic and M. J. Strassler, Phys. Rev. D **84** (2011) 035012 [arXiv:1103.2127 [hep-ph]]; S. Y. Ayazi, S. Khatibi and M. Mohammadi Najafabadi, arXiv:1205.3311 [hep-ph]; J. Cao, K. Hikasa, L. Wang, L. Wu and J. M. Yang, Phys. Rev. D **85** (2012) 014025 [arXiv:1109.6543 [hep-ph]].

[9] B. Grinstein, C. W. Murphy, D. Pirtskhalava and P. Uttayarat, arXiv:1203.2183 [hep-ph].

[10] E. Gabrielli, M. Raidal and A. Racioppi, arXiv:1112.5885 [hep-ph]; E. L. Berger, Q. -H. Cao, C. -R. Chen, J. -H. Yu and H. Zhang, arXiv:1111.3641 [hep-ph].

[11] L. Wang, L. Wu and J. M. Yang, Phys. Rev. D **85** (2012) 075017 [arXiv:1111.4771 [hep-ph]].

[12] A. Djouadi, G. Moreau, F. Richard, and R. K. Singh (2009), 0906.0604.

[13] Z. Ligeti, M. Schmaltz and G. M. Tavares, JHEP 1106, 109 (2011); J. Shu, T. M. P. Tait and K. Wang, Phys. Rev. D 81, 034012 (2010); A. Arhrib, R. Benbrik and C. H. Chen, Phys. Rev. D 82, 034034 (2010); I. Dorsner, S. Fajfer, J. F. Kamenik and N. Kosnik, Phys. Rev. D 81, 055009 (2010); Phys. Rev. D 82, 094015 (2010).

[14] B. Grinstein , A. L. Kagan, M. Trott and J. Zupan, Phys. Rev. Lett. 107, 012002 (2011);K. M. Patel and P. Sharma, JHEP 1104, 085 (2011).

[15]

[15] S. Khatibi and M. Mohammadi Najafabadi, arXiv:1207.6689 [hep-ph].

[16] I. L. Shapiro, Phys. Rept. **357** (2002) 113 [hep-th/0103093].

[17] G. de Berredo-Peixoto, J. A. Helayel-Neto and I. L. Shapiro, JHEP **0002** (2000) 003 [hep-th/9910168].

[18] I. L. Buchbinder and I. L. Shapiro, Class. Quant. Grav. **7** (1990) 1197.

[19] D0 Collaboration, Phys. Lett. B 704, (2011) 403-410.

[20] The CMS Collaboration, CMS-PAS-TOP-11-024.

[21] U. Langenfeld, S. Moch, and P. Uwer , Phys. Rev. D. 80, 054009 (2009), [arXiv:0906.5273[hep-ph]]; M. Cacciari et al. , JHEP 09, 127 (2008), [arXiv:0804.2800[hep-ph]]; N. Kidonakis and R. Vogt , Phys.

Rev. D. 78, 074005 (2008), [arXiv:0805.3844 [hep-ph]]; V. Ahrens, A. Ferroglia, M. Neubert, B. D. Pecjak and L. Li , JHEP 09, 097 (2010), [arXiv:1003.5827[hep-ph]].

[22] R. Kleiss andW. J. Stirling, Z. Phys. C40 (1988) 419423. doi:10.1007/BF01548856; A. D. Martin,W. J. Stirling, R. S. Thorne et al, Eur. Phys. J. C63 (2009) 189285, arXiv:0901.0002; A. D. Martin,W. J. Stirling, R. S. Thorne et al, Eur. Phys. J. C64 (2009) 653680, arXiv:0905.3531; H.-L. Lai, J. Huston, Z. Li et al, Phys.Rev. D82 (2010) 054021, arXiv:1004.4624; F. Demartin, S. Forte, E. Mariani et al, Phys. Rev. D82 (2010) 014002, arXiv:1004.0962.

[23] A. D. Martin, W. J. Stirling, R. S. Thorne and G. Watt, Eur. Phys. J. C **63** (2009) 189 [arXiv:0901.0002 [hep-ph]].

[24] G. Aad et al. [ATLAS Collaboration], arXiv:1203.4211 [hep-ex].

[25] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **709** (2012) 28 [arXiv:1112.5100 [hep-ex]]; S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **717** (2012) 129 [arXiv:1207.0065 [hep-ex]].

[26] [23] J. H. Kuhn and G. Rodrigo, JHEP 1201, 063 (2012).

[27] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **704** (2011) 123 [arXiv:1107.4771 [hep-ex]].

[28] T. Aaltonen *et al.* [CDF Collaboration], arXiv:1211.1003 [hep-ex].

[29] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **102** (2009) 222003 [arXiv:0903.2850 [hep-ex]].